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# Estimation of uncertainties in CT metrology by simulation

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*Publication date:*
2011

*Document Version*
Publisher's PDF, also known as Version of record

# Estimation of uncertainties in CT metrology by simulation

CT Audit
University of Padova, October 26th


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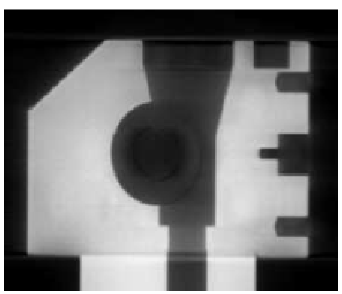
Department of Mechanical Engineering

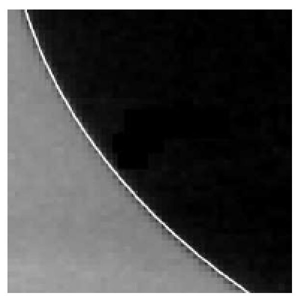
# Content

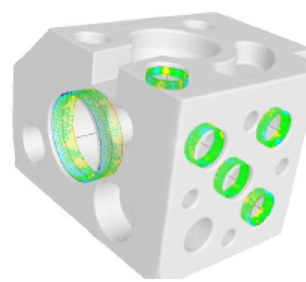
- Motivation and problem definition
- The proposed approach
- Modelling and analytical simulation of CT scanning process
- Case study: Uncertainty estimation at a simple workpiece
- Summary and outlook

# Motivation and problem definition

| CT | Image processing | Coordinate measurement | Measurand |
|---|---|---|---|
| **Reconstruction Image quality** | **Surface determination** | **Coordinate measurement in 3D model** | **Determination of dimension, form, and position** |





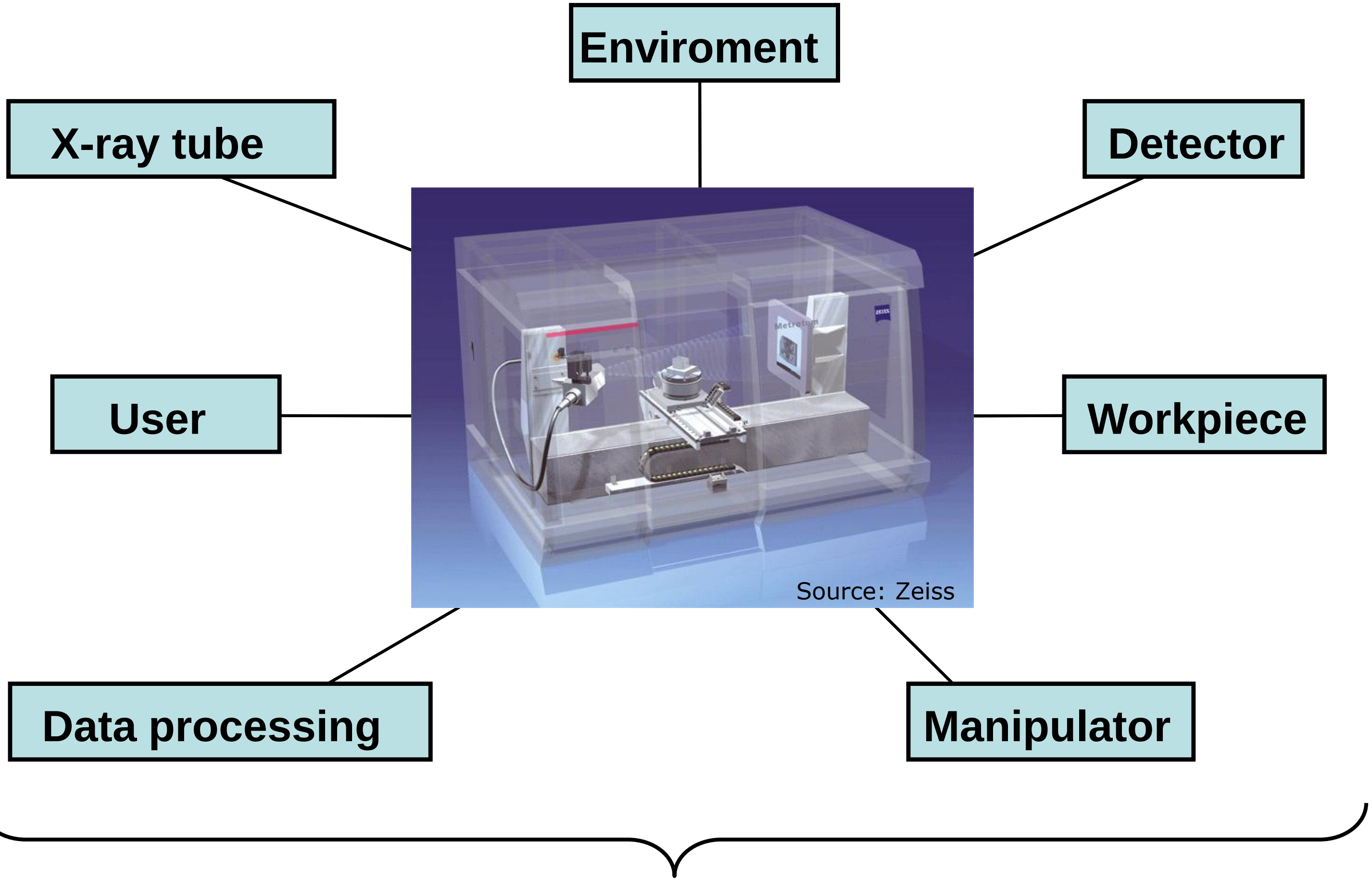


$Ø_1$ = 15,24 mm

$Ø_2$ = 18,87 mm

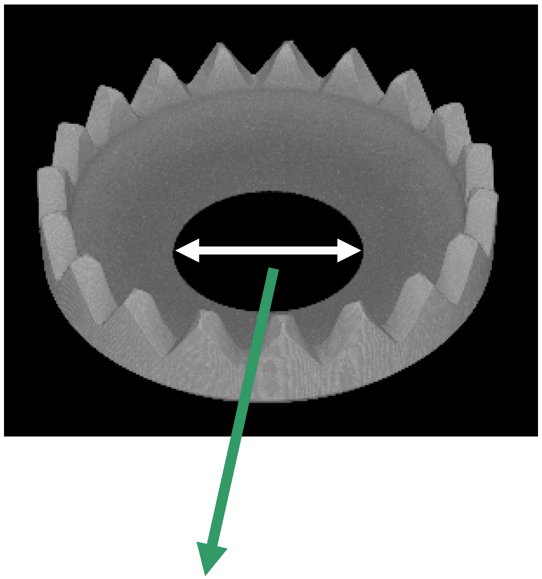
***Uncertainty*?**

# Motivation and problem definition




*Influences lead to systematic and random measurement errors*

# Motivation and problem definition



Ø: 2,424 mm ± ???

- **Analytical calculation**
  - almost not possible in CT
- **Experimental method**
  - calibrated workpiece available?
  - Destruction of the workpiece?
  - repeated measurements (time-factor)
- **Simulation method**
  - "virtual experiments" using computers
  - numerical evaluation of measurement uncertainty
  - Basis: Monte Carlo method (MCM)

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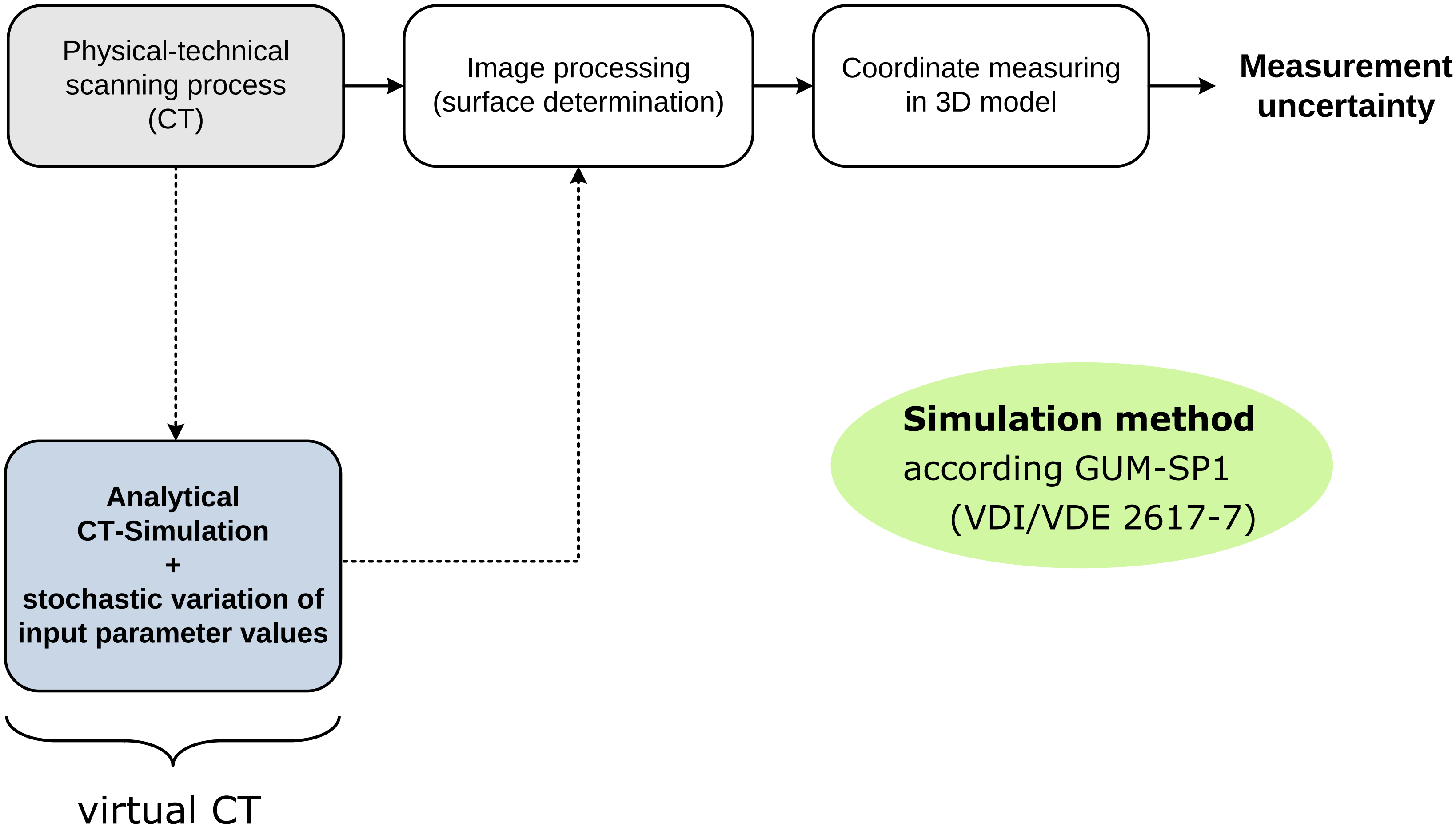
# The proposed approach



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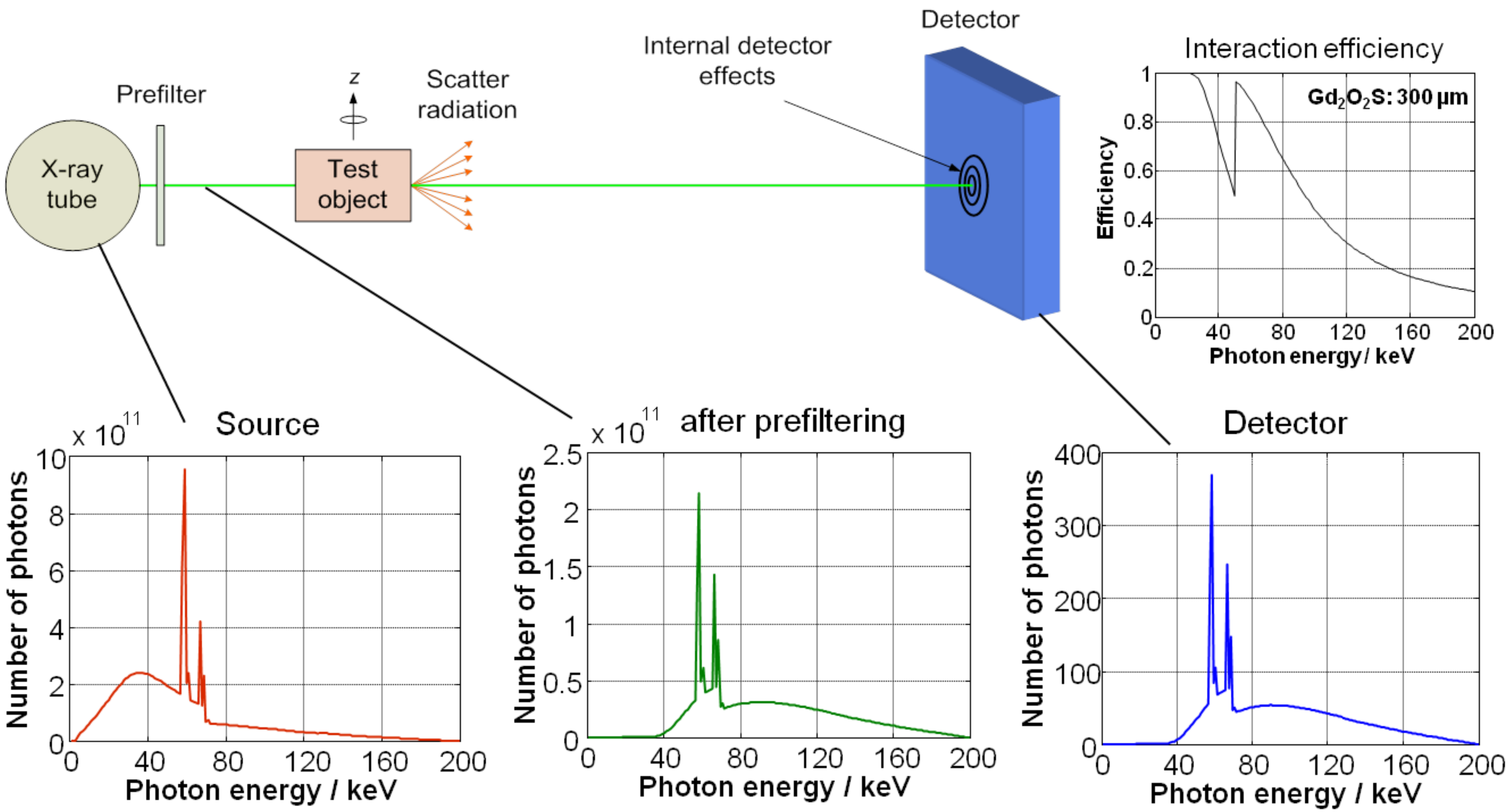
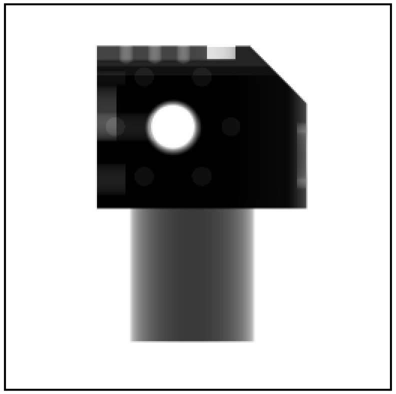
# Modelling and analytical simulation

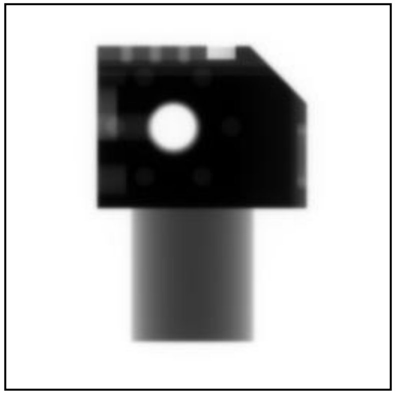


# Modelling and analytical simulation



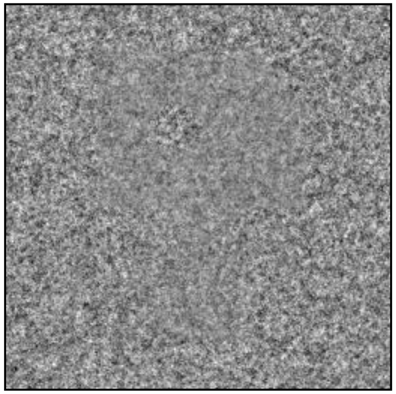
Expected pixel
signal image

***unsharpness***

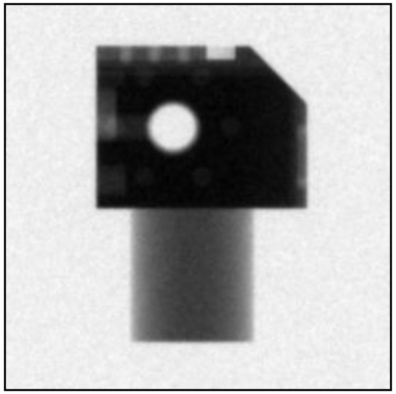


- **Detector unsharpness**
- **Focal spot size & drift**
- **Object scatter radiation**
- **Detector/rotation axis misalignment**
- **Detector afterglow**

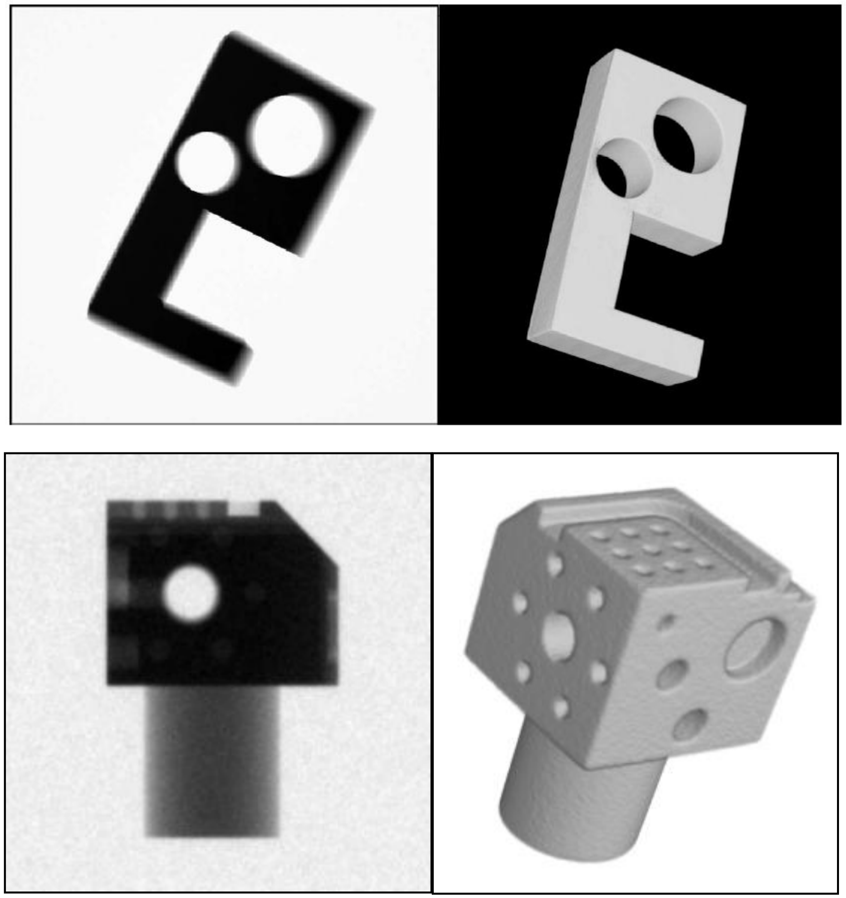
***noise***



**Spatial variant &
correlated image noise
(quamtum + electronic)**



# Modelling and analytical simulation



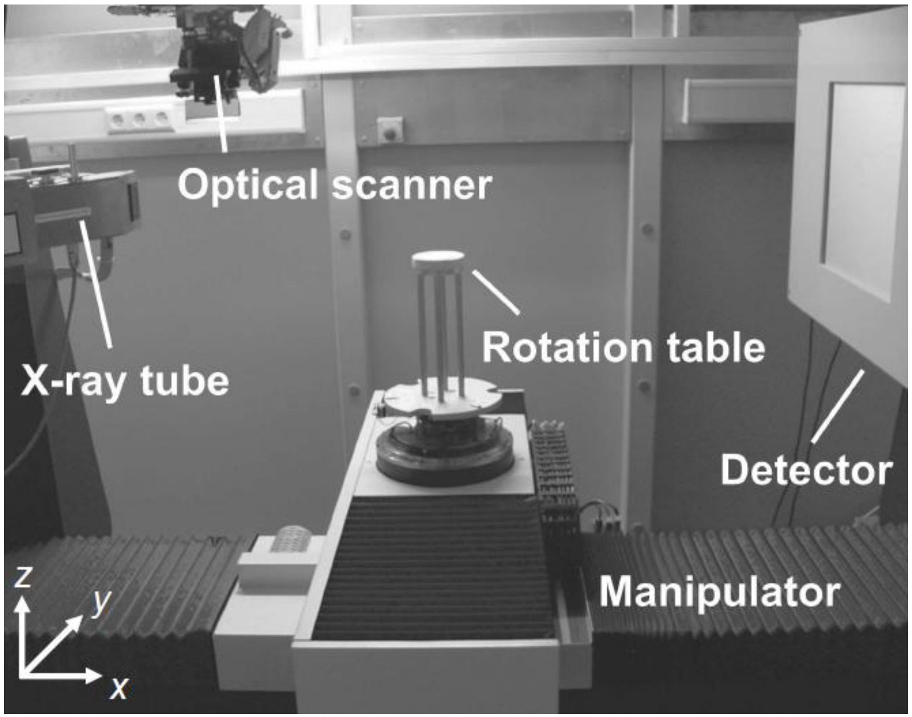
Projection CT model

- **Consideration of**
  - Image unsharpness
  - Image noise
  - Image artefacts (beam-hardening, scatter radiation)
  - System misalignment including temporal focus drift
  - Environment influences (temperature)
  - *Random variability of input quantities*

**virtual CT**

# Modelling and analytical simulation

Tomolibri® Micro-CT system

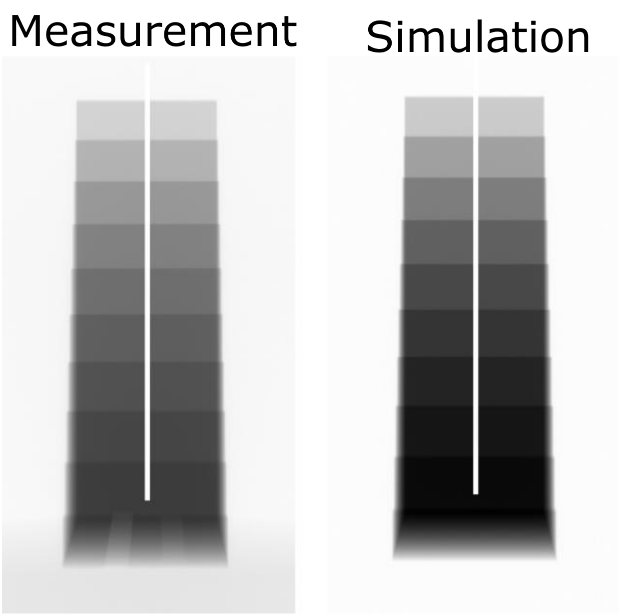


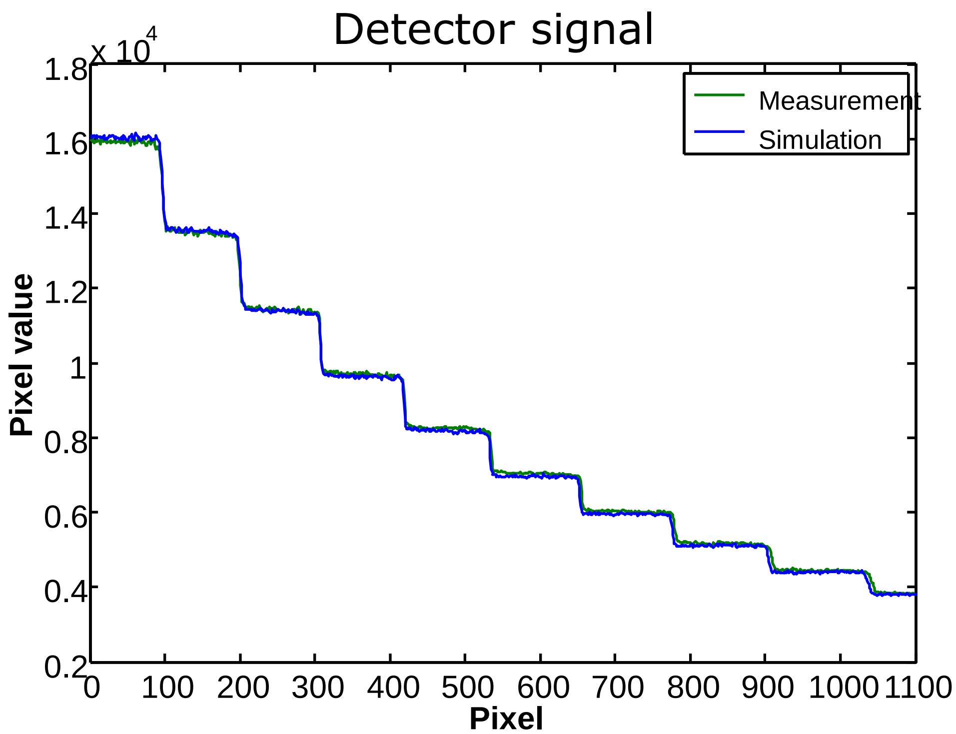

- **Relevant information**
  - Focal spot size
  - Focus drift
    (in 3 dimensions if possible)
  - Detector contrast & noise transmission
  - System misalignment parameters

**By characterization measurements**

# Modelling and analytical simulation

*First validation of synthetic projection images using simple test objects like step-wedges*



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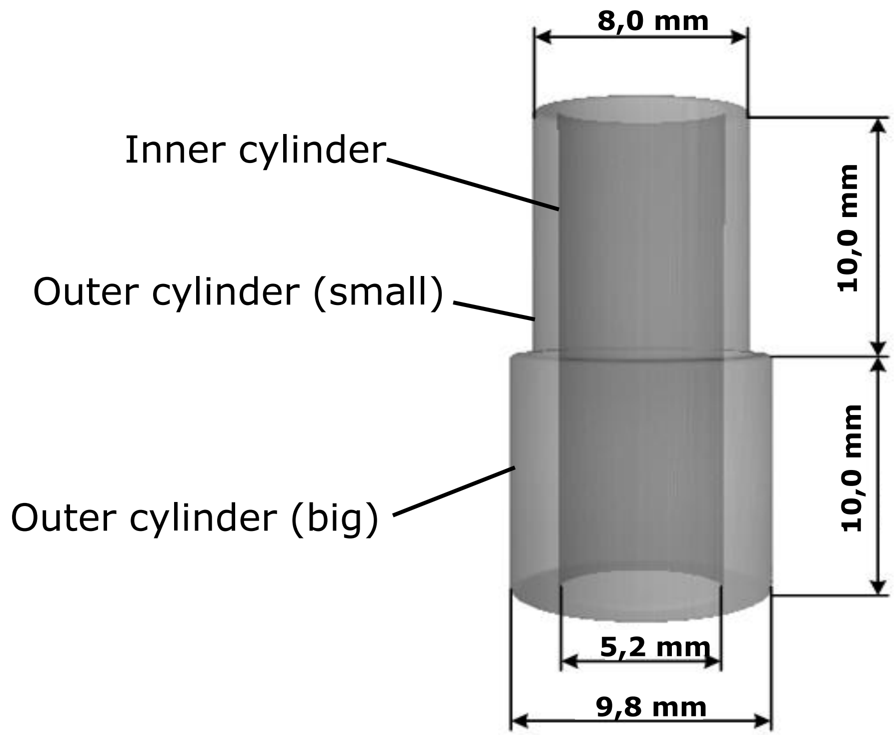
# Case study

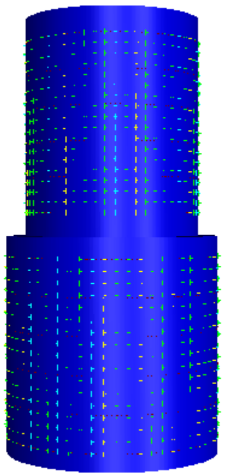
Material: X20Cr13 (Steel)



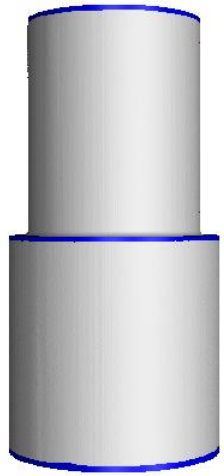

**Measuring tasks:**

- Evaluation of the 3 cylinder diameters
- Evaluation of associated form deviations of the cylindrical geometries

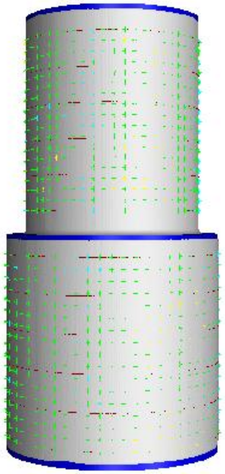
# Case study



Measuring points
on CAD model



Registration
with CT model



Evaluation of spatial
3D coordinates & fitting

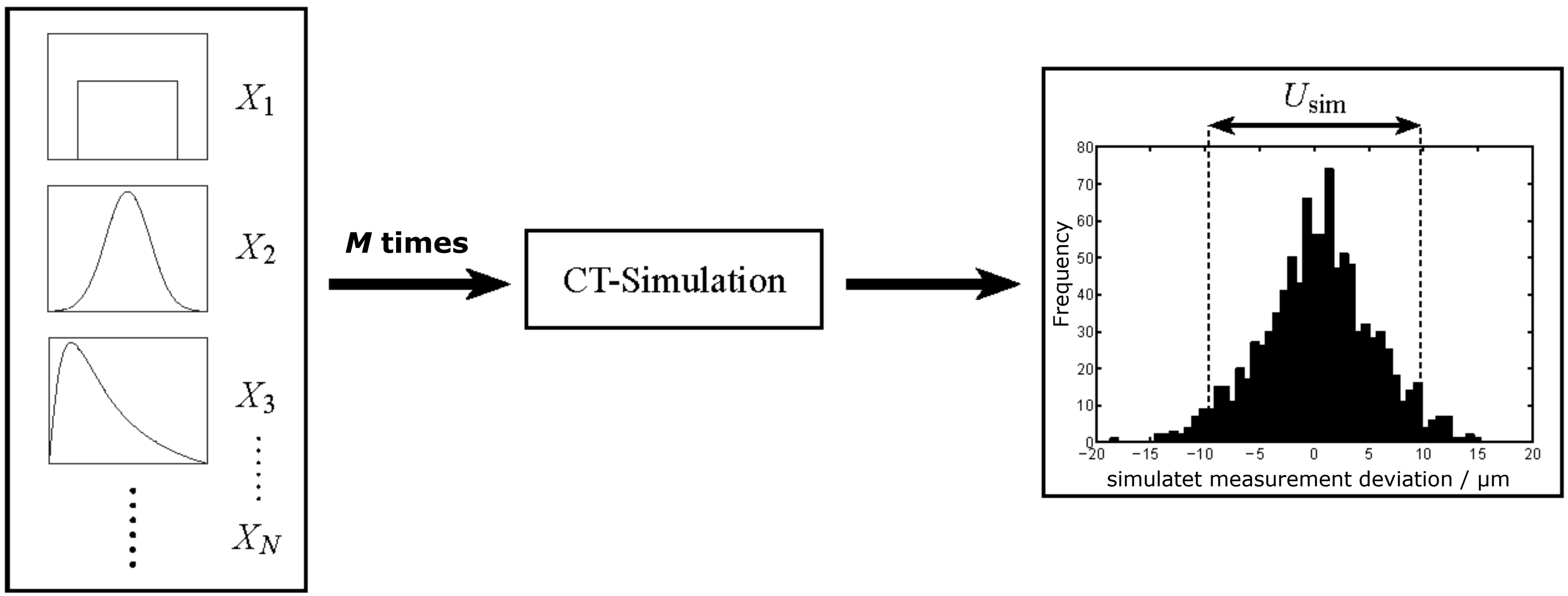
**Result**

**Result of dimensional CT measurements:**

| Geometry element | Diameter in mm | Form deviation in µm |
|---|---|---|
| Outer cylinder, small | 8,014 | 8 |
| Outer cylinder, big | 9,812 | 9 |
| Inner cylinder | 6,192 | 21 |

# Case study

**Stochastic variation of input parameter values**




**Input quantities** **Model of CT** **Output quantity**

# Case study

| | Parameter | Default | Uncertainty | Range of values |
|---|---|---|---|---|
| X-ray tube | $U_R$ | 200 | 1 % | 198 … 202 |
| | $I_R$ | 0,1 | 5 % | 0,095 … 0,105 |
| | $\alpha_T$ | 15,0 | 33,3 % | 10,0 … 20,0 |
| | $B_h$ | 54,0 | 5 % | 51,3 … 56,7 |
| | $B_v$ | 50,0 | 5 % | 47,5 … 52,5 |
| | $D_{h_1}$ | $8{,}45 \cdot 10^{-3}$ | 42,0 % | $(4{,}9 \ldots 12{,}0) \cdot 10^{-3}$ |
| | $D_{h_2}$ | 2,85 | 19,3 % | 2,3 … 3,4 |
| | $D_{v_1}$ | $4{,}03 \cdot 10^{-3}$ | 20 % | $(3{,}2 \ldots 4{,}8) \cdot 10^{-3}$ |
| | $D_{v_2}$ | 1,95 | 18 % | 1,6 … 2,3 |
| Geometry | $\Delta x_{det}$ | 0,0 | 0,2 Pixel | −40,0 … 40,0 |
| | $\Delta y_{det}$ | 0,0 | 0,2 Pixel | −40,0 … 40,0 |
| | $\eta_{det}$ | 0,0 | 0,1° | −0,1 … 0,1 |
| | $\phi_{det}$ | 0,0 | 1,0° | −1,0 … 1,0 |
| | $\theta_{det}$ | 0,0 | 0,5° | −0,5 … 0,5 |
| | FDA | 1539,447 | 1 % | 1524,052 … 1554,841 |
| | FOA | 114,953 | 0,3 % | 114,608 … 115,298 |
| Position | $T_x$ | 0,0 | 0,5 mm | −0,5 … 0,5 |
| | $T_y$ | 0,0 | 0,5 mm | −0,5 … 0,5 |
| | $T_z$ | 0,0 | 0,5 mm | −0,5 … 0,5 |
| | $R_x$ | 0,0 | 1,5° | −1,5 … 1,5 |

$U_{ct}$

*Uniform distributed input quantities assumed*

Number of simulations $M = 50$

# Case study

Result: $\boxed{U = U_{sim} = U_{ct}}$

- If uncertainty contribution $u_1 \dots u_i$ from other sources avaliable (hybrid):

$$\boxed{U = k \cdot \sqrt{u_1^2 + \ldots + u_i^2 + u_{\mathrm{sim}}^2}} \quad \text{with} \quad \boxed{u_{\mathrm{sim}} = \frac{U_{\mathrm{sim}}}{k}}$$

- If uncertainty contribution $u_{sim_1} \dots u_{sim_j}$ from simulation can be seperated

→ *no correlations among single contributions* $u_{sim_1} \dots u_{sim}$:

$$\boxed{U = k \cdot \sqrt{u_1^2 + \ldots + u_i^2 + u_{\mathrm{sim}_1}^2 + \ldots + u_{\mathrm{sim}_j}^2}}$$

# Case study

Completed result:

$$\boxed{Y = y \pm U}$$

- Diameter:

| Geometry element | *U* (95 %) in mm | *U* (99 %) in mm | *Y* (95 %) in mm | *Y* (99 %) in mm |
|---|---|---|---|---|
| Outer cylinder, small | 0,080 | 0,086 | 8,014 ± 0,080 | 8,014 ± 0,086 |
| Outer cylinder, big | 0,102 | 0,108 | 9,812 ± 0,102 | 9,812 ± 0,108 |
| Inner cylinder | 0,064 | 0,066 | 6,192 ± 0,064 | 6,192 ± 0,066 |

- Form deviation:

| Geometry element | *U* (95 %) in µm | *U* (99 %) in in µm | *Y* (95 %) in µm | *Y* (99 %) in µm |
|---|---|---|---|---|
| Outer cylinder, small | 3 | 3 | 8 ± 3 | 8 ± 3 |
| Outer cylinder, big | 4 | 4 | 9 ± 4 | 9 ± 4 |
| Inner cylinder | 6 | 9 | 21 ± 6 | 21 ± 9 |

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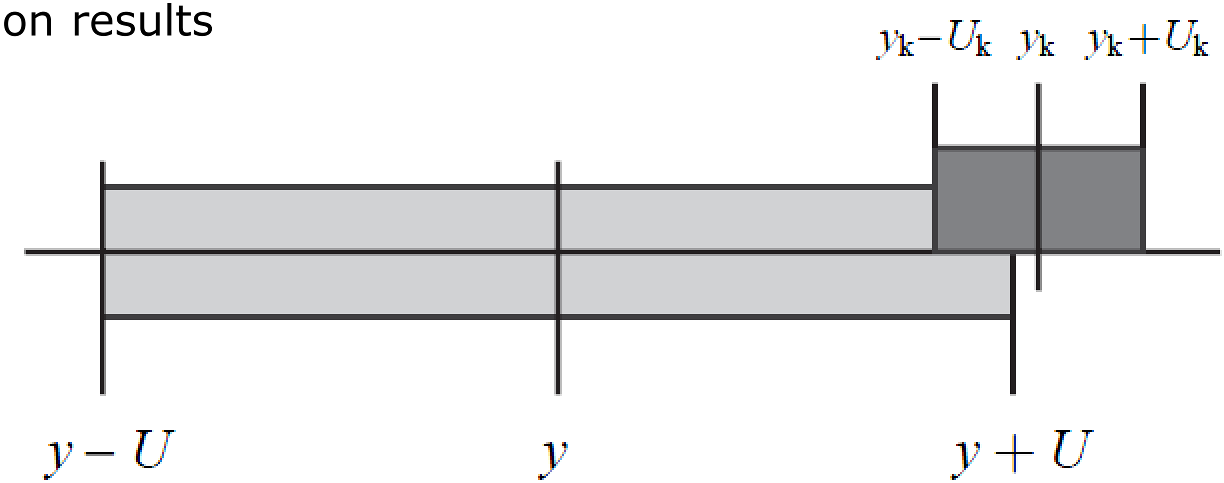
# Summary and outlook

- *A simulation-based method to estimate uncertainties in dimensional CT using synthetic X-ray projection data and the Monte Carlo method, combined in the virtual CT, was presented*

- **Further developments should be concentrated on:**
  - Increasing of computational performance to increase the number of simulations
  - Development of systematic workflow for characterization of a CT system to adapt the simulation enviroment
  - Minimization of input quantities to the most significant ones and studying of correlations
  - Development of procedures to validate CT simulators in 2D/3D

# Summary and outlook

- Usage/development of procedures to validate the simulation results




Test of plausibility according to VDI/VDE 2617-7

using calibrated workpieces:

$$\boxed{|y_k - y| \le (U_k + U)}$$

**calibrated value** | **measured value** | **Calibration uncertainty** | ***Uncertainty by simulation***

Thank you for your attention